LUMINESCENT BOLOMETER AND NEUTRINO PHYSICS

L. GONZALEZ-MESTRES

Laboratoire d'Annecy-le-Vieux de Physique des Particules,
B.P. 1110 , 74941 Annecy-le-Vieux Cedex, France

and

Laboratoire de Physique Corpusculaire, Collège de France,
11 place Marcellin-Berthelot, 75231 Paris Cedex 05 , France

The luminescent bolometer, proposed in 1988 , is now seriously considered for several applications in nuclear and particle physics: dark matter searches, double beta decays, low energy neutrino physics, heavy ion physics... It is also a very promising device for basic condensed-matter physics and chemistry experiments, and may lead to astrophysical applications. The luminescent bolometer is based on the simultaneous detection of light and phonons, allowing for particle identification and for a detailed study of the detector response. Digitized analysis of the signals produced in several sensors installed on the same crystal is then a very powerful tool. Superconducting sensors allow to detect the scintillation light pulse followed by the delayed front of phonons, and can be extremely sensitive leading to single photon counting in the visible range. They also provide information on the position of the event inside the absorber, and can be fast enough for all proposed applications. The luminescent bolometer, with superconducting sensors, appears extremely promising for real time *solar neutrino experiments* based on new *indium* single crystal scintillators. We focus on this particular application, discussing the status of the art as well as open problems and presenting an updated description of a full scale real time solar neutrino experiment sensitive to the low energy sector.

Other applications of the luminescent bolometer (e.g. spectroscopy or neutrino detection at reactors), involving indium compounds and other single crystal scintillators, are equally considered and discussed in detail.

1. The Luminescent Bolometer

Simultaneous detection of light and phonons in a single crystal scintillator cooled to very low temperature was proposed in 1988 [1] as a new tool for particle detection. The new technique was expected to: a) provide slow thermal detectors with a fast light strobe, allowing for a much better timing without crucially spoiling energy resolution; b) make possible particle identification through the phonon/light ratio, thus improving background rejection. As thermal bolometers evolve nowadays towards the detection of nonequilibrium phonons, fluorescence appears as a natural complement. Many crystals are expected to produce an important light yield at very low temperature. The device operating simultaneous detection of light and phonons at very low temperature was called the *luminescent bolometer* [2]. Simultaneous detection of fluorescence light and nonequilibrium phonons would allow [3,4] to combine good energy resolution, fast timing, position information and high background rejection, leading to a new generation of very performant devices. Several extremely difficult experiments may become feasible, whereas a certain number of present day experiments would be seriously improved by the new cryogenic device.

A number of well-known scintillators (BGO, $CdWO_4$, $CaWO_4$, GSO:Ce, CeF_3 , YAG:Ce, CaF_2:Eu...) exhibit fast luminescence at low temperature and are serious candidates for absorbers. But other substances, which do not scintillate at room temperature, become efficient luminophores when cooled down as thermal quenching disappears. Two examples may be particularly relevant to particle detection:

a) $PbMoO_4$ green fluorescence is known [5,6] to increase by four orders of magnitude between room temperature and LN_2 temperature. Its fluorescence properties have been studied down to He_4 temperature [6]. Following a proposal to apply cooled $PbMoO_4$ to double beta experiments [7], a $PbMoO_4$ $2 \times 2 \times 2$ cm^3 single crystal read by a photomultiplier through a quartz light guide was characterized down to LN_2 temperature and showed a photopeak pulse height equal to 16% of that of room temperature NaI:Tl [8].

b) Some indium oxides studied by J.P. Chaminade [9] following a proposal [10,11,4] to develop a scintillating single crystal incorporating ^{115}In as a basic element, exhibit encouraging scintillating properties at low temperature. An example is $In_2Si_2O_7$ [10,12] which has been characterized down to 4K [12], and many other compounds can be considered [10].

If the properties of the absorber (Debye temperature, phonon propagation, low temperature scintillation light yield and decay time...) are crucial to the quality of a luminescent bolometer, the sensors are equally key elements. The firts design proposed [1,2] the use of separate sensors for the light and the phonons. Semiconductors, thin black bolometers and superconductors were considered as photon sensors [1,2,11]. The first successful feasibility study, made by the Milano group, adopted such an approach [13,14] using a photodiode as the cryogenic photosensitive device. This practical solution allowed to demonstrate the principle without previously undertaking long technical developments. The results were naturally limited in threshold and energy resolution, as has been discussed in recent reviews [15,16], but the situation can be improved. In 1991 , we proposed [3,4] a new design incorporating: a) a common sensor for both the light strobe and the delayed phonon signal;

b) the use of arrays of superconducting tunnel junctions (STJ) as the new sensor.

2. Relevance of superconducting sensors

Superconductors are natural sensors for both phonons and photons, and should perform better than semiconductors due to the comparatively low gap for quasiparticle excitation. Low impedance superconducting films already provide the best phonon sensors [17], and photosensitive superconducting devices are an active research subject [18]. A performant superconducting sensor, sensitive to the light strobe followed by the delayed pulse of phonons, would considerably simplify and improve the architecture of the luminescent bolometer. This seems feasible nowadays due to the success of arrays of superconducting tunnel junctions [19] and of other superconducting sensors [20]. The new device, made of a single crystal low temperature scintillator with an appropriate superconducting sensor implanted on each of its faces, may become the ultimate detector for several physics goals.

2a. STJ arrays

With a series array of 432 Al-Al STJ, implanted on a Si wafer with an area of 12 $\times$ 12 mm^2 and a thickness of 0.5 mm, the Oxford group obtained [19] at T $\simeq$ 360 mK (base temperature of the cryostat) a resolution of 700 eV FWHM on a 25 keV X-ray peak produced from the fluorescence of an indium foil. A naive extrapolation suggests [3,4] that a similar STJ array could be sensitive to $\approx$ 1 keV of photons absorbed near the array, which corresponds to the light yield of a $\approx$ 10 keV electron or photon in an efficient scintillator. According to the Oxford group[19], most of the 25 keV peak width was due to drifts in the cryostat temperature and to electronic noise. These considerations motivated our proposal to use arrays of STJ for the detection of both photons (the fast strobe) and phonons (the delayed pulse). To absorb the scintillation light we considered, either implanting a thin layer between the radiation absorber and the STJ array (but care must be taken of phonon propagation through the layer), or to use blackened STJ arrays covering a large fraction of the crystal surface (which requires working in an optical cavity).

An interesting possibility would be to deposit the STJ arrays on a superconducting substrate of higher critical temperature, covering the full crystal surface (an array per face). Nb or Sn can be the substrate for a Al STJ array. Thus, both the photons and the phonons from the absorber would be converted into quasiparticles by the substrate layer in an efficient way. Such quasiparticles would subsequently be detected by the STJ array. The photon signal would immediately originate in the substrate, whereas phonons would first undergo a number of scattering processes depending on the size and quality of the crystal. With an ADC and a DSP after the electronic chain, for each face of the crystal, digital analysis would allow to reach a very low threshold for both the fluorescence and the phonon signal. It should be noticed that, when the expected signal is a sum of exponentials, on-line digital filtering allows for iterative algorithms leading to very performant trigger schemes [21], which apply to fluorescence in a straightforward way and can be adapted to phonon detection. Energy resolution would also be very good, as total energy can be reconstructed

from light and phonon pulses. Digital analysis of the phonon pulse would lead to excellent space resolution inside the crystal. Timing would depend on the fluorescence properties and on the superconducting read-out, but it seems reasonable to expect to reach fast timing (down to 100 ns) with suitable choices. However, the crystal size and phonon scattering properties will necessarily set an intrinsic limit to the detector performance. Phonons reaching the crystal surface with an energy $E < 2\Delta$ (the gap of the STJ superconducting material) cannot contribute to the signal.

Even if the scheme and goals are not identical, it is worth noticing that Perryman et al. propose[22] optical photon counting with a superconducting substrate in combination with an array of widely spaced STJ of lower energy gap. In our case, we are not interested in optical photon counting but in the detection of 10^2 - 10^5 optical photons produced by a particle interacting with the cooled scintillator. On the other hand, we must face the extra requirement of efficient phonon detection from large absorbers. The fact that several intrinsic scintillators work at low temperature is encouraging, as doped scintillators may exhibit poor phonon propagation. An attempt to model non-equilibrium signals in a series array of STJ has recently been performed by the Oxford group [23].

2b. Other techniques

Superconducting films are very successful [17,24] and solutions based on this technique, others than STJ arrays, deserve serious consideration. But efficient detection of scintillation light is likely to limit the freedom of the design. It is possible to consider superheated superconducting dots[25] when only four faces of the crystal need to be used (allowing for a magnetic field parallel to the four faces), or for cylinder structures. But this may limit space resolution. Sensitivity may also be a problem. It seems difficult to simultaneously detect light and external phonons using superheated microspheres, but we may hope for technical progress in the interface between the granules and the scintillating absorber.

2c. A critical remark

Although luminescence properties are not expected to drastically change between 4K and dilution temperatures, it must be noticed that only two experiments [13,14,26] have studied the luminescence of a thermal bolometer cooled to very low temperature, and only one of them [13,14] incorporated a sensor for the scintillation light. Many more experiments are required on luminescence at very low temperature before setting the design of a superconducting sensor for light and phonons. However, STJ arrays present the advantage of operating with excellent performances at He_3 and even at He_4 temperatures, which simplifies several basic problems. Simultaneous detection of light and phonons presents a similar advantage as compared to simultaneous detection of ionization and heat.

3. Proposed applications

3a. Non-baryonic dark matter

This was the first proposed application of the luminescent bolometer [2], in view of background rejection and nucleus recoil identification. The approach has recently been criticized on the grounds of the high threshold of existing prototypes [16], but as has been explained in this paper the present situation can be considerably improved introducing superconducting sensors: then the threshold of the luminescent bolometer will become as low as that of any device performing simultaneous detection of ionization and heat. The possibility to work well above dilution temperatures will then become a definite advantage of dark matter experiments using the luminescent bolometer. The reliability of a large scale experiment would be much better with our approach, where 100 kg to 1 ton detectors can indeed be cooled to the operating temperature with existing and well established cryogenic techniques. Furthermore, targets such as ^{7}Li, ^{19}F, ^{27}Al, ^{127}I, ^{183}W... can be incorporated in the cold scintillator approach. If particle physics and cosmology still provide a ground to experiments aiming at the direct detection of dark matter WIMPs (there is to date no evidence for new particles!), the luminescent bolometer with a superconducting read-out is to be the right technique for that purpose. However, many basic studies remain to be performed on the low temperature behaviour of the relevant scintillators.

3b. Double beta

Applications to double beta experiments were proposed in 1989 [7], with the idea to reject the alpha background in high Q materials. $CdWO_4$ and $PbMoO_4$ were then explicitly considered. The use of $CdWO_4$ seems indeed to be a promising way [27,15]. To our original proposal, the Milano group has added the successful development of a CaF_2 luminescent bolometer [13,14]. The use of superconducting sensors would be crucial to improve energy resolution, allowing for: a) a better background rejection (rejection of α's, but also eventually separation between β or γ and 2β events); b) eventually, the necessary separation in energy between the tail of double beta decays with neutrinos and neutrinoless double beta events, feasible only through energy resolution and possibly through a careful analysis of the phonon pulse sensitive to the details of electron energy losses. Comparison between the fluorescence and the phonon pulse will be crucial, not only because of phonon/light ratio but also through the study of the delay between both pulses on the six faces of the crystal. With these tools, a molybdenum experiment using a molybdate cooled to very low temperature should be seriously considered. After suitable technical developements, the luminescent bolometer can potentially incorporate any double beta target. The elementary cells of a double β experiment can be $\approx 2 \times 2 \times 2$ cm^3 crystals, which amounts to ≈ 25 crystals and ≈ 150 electronic channels per Kg of detector.

3c. Solar and reactor neutrinos (indium target)

This may become the most important and far-reaching application of the luminescent bolometer, as no technique allows by now to detect in real time low energy neutrinos. Recent progress on indium single crystal scintillators is encouraging [9], but it is unlikely that a room temperature scintillator would lead to a correct background rejection[3,4]. 2β and 3β coincidences from ^{115}In radioactivity, as well as coincidences between a ^{115}In β and an erratic gamma, are the main worries for a solar neutrino detector with a ^{115}In target.

5

Room temperature scintillation does not seem to provide enough information to fight such a background, but detecting phonons in addition would considerably improve space and energy resolution, which are crucial to evaluate the detector performance.

Several indium compounds seem to scintillate mainly at low temperature. To the indium germanates, silicates and other oxides presently under study, some of which (e.g. $In_2Si_2O_7$) give excellent results at low temperature, InCe oxides should be added in order to possibly exploit the fluorescence of trivalent cerium. Fluorides deserve further consideration[9,10], as some of them can scintillate and crystal growth seems easier than with oxides. A large scale, real time solar neutrino experiment based on Raghavan'as reaction, with a luminescent bolometer made of an indium compound, has already been described [3,4,28] and nothing to date contradicts its potential feasibility. With $\approx$ 1cm space resolution in $4 \times 4 \times 4$ cm^3 single crystals, segmentation in a few million elementary cells would be achieved, allowing for a signature based on the triple coincidence between the [115] β and the two, spatially separated, delayed γ's (116 and 496 keV). But the large number of crystals ($\sim 3.10^4$) and electronic channels ($\sim 2.10^5$) required, with on line digital analysis, makes it a great challenge even if the appropriate scintillating crystals become available.

A neutrino-antineutrino oscillation experiment at a reactor would be $\sim$ 100 times smaller. It must therefore be considered as a preliminary step, working at a higher neutrino energy (higher inverse β energy) which should considerably simplify the above discussed background rejection. On the other hand, ambient background is much worse and deserves a careful study where self-sheilding (active) is likely to play a crucial role.

The possibility to actually find performant intrinsic indium single crystal scintillators is real and exciting [9]. Such a breakthrough would considerably improve the prospects for phonon detection in large scintillating indium crystals. However, light yield and fluorescence lifetime under β and γ irradiation remain a challenge, as very sharp performances are required in the proposed experiments. Superconducting sensors appear as the only solution to build a feasible detector, satisfying all requirements in view of background rejection.

3d. Other applications

Basic physics and chemistry, as well as nuclear physics and technology, are generating many potential applications of the luminescent bolometer. The study of relaxation phenomena would considerably benefit from such a progress in instrumentation, allowing to detect in real time several components of the degraded energy. Nuclear spectroscopy requiring particle identification (phonon analysis may even allow to distinguish between a β and a γ inside a crystal), neutron detection at low counting rate (e.g. with a lithium target[3,26]), low radioactivity measurements including study and detection of long lived isotopes... are applications of increasing interest in both scientific and industrial domains, where detector performance can be combined with self-shielding[3] potentialities. Heavy ion physics also appears as an ideal domain for the new device [28], as the luminescent bolometer may replace with success all kinds of detectors of present-day experiments (semiconductors, scintillators, forward detectors...). The luminescent bolometer may become relevant to nuclear and particle physics and technology, astrophysics and space science and tech-

nology, material science, environment, biology and medical uses. Superconducting sensors as well as on line digital analysis are essential tools to fully exploit the potentialities of a detector whose basic performance will be the ability to record in real time a large amount of physical information on the interaction of particles with matter.

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